

Influence of Volatile Content on the Explosion Characteristics of Coal Dust

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Cite This: *ACS Omega* 2021, 6, 27150–27157



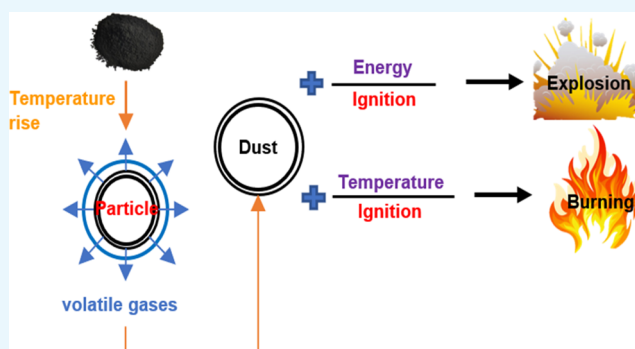
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ABSTRACT: To study the influence of different volatile contents on the explosion characteristics of coal dust, the volatile content in coal dust was controlled under different final temperatures of pyrolysis. The maximum explosion pressure, maximum pressure rising rate, and explosion index were used to characterize the pressure behavior, the pressure ratio to characterize the explosibility, and the minimum ignition temperature of the coal dust cloud to characterize the sensitive characteristics. A 20 L of nearly spherical coal dust explosion parameter measuring device and a dust cloud minimum ignition temperature measuring device were used to study the influence of the explosion characteristics of dust with different volatile contents prepared under different pyrolysis temperature conditions. The results showed that the volatile matter content in lignite dust has little effect on the maximum explosion pressure, with an average change rate of 5.435%. When the volatile content was reduced from 45.4 to 2.45%, the maximum explosion pressure rise rate dropped by 65.976%. The explosion index of the experimental sample was in the range of 0–1.6, with weak explosion characteristics; the lower the volatile content, the weaker the explosion intensity. When the volatile content was only 2.45%, the pressure ratio was still greater than 2, that is, the dust was still explosive. When the volatile content in lignite was reduced from 45.4 to 18.21%, the lowest ignition temperature of the dust cloud was consistently 490 °C. At this stage, the contents of H₂, CO, CH₄, CO₂, and other precipitated gases were low. When the volatile content was reduced from 18.21 to 2.45%, the precipitated volatile gas increased rapidly, the remaining precipitated gas content decreased, and the dust could not be easily ignited. The experimental results lay the foundation for studying the influence mechanism of volatile matter in coal dust on the explosion characteristics.



1. INTRODUCTION

As China's main energy source, coal has an important role in improving the economy, and its efficient and reasonable development and utilization have an irreplaceable strategic position. However, during the preparation and storage of pulverized coal in coal mines, coal chemical industries, and thermal power and metallurgical industries, the hidden dangers of coal dust explosions¹ seriously threaten the safety of industrial production. Coal dust flies up under the action of an external force to form a certain concentration of cloud clusters. When the cloud cluster concentration reaches the explosive concentration range conditions, fires or explosions can easily occur. The temperature rise during the production process also causes the coal dust to accumulate in the layers to ignite spontaneously and even evolve into an ignition source that can cause an explosion or fire.²

The explosion of the dust can be mainly characterized by the explosion intensity characteristics and explosion sensitivity.³ The intensity characteristics of dust explosion reflect the violent degree of the explosion, characterized by the maximum explosion pressure of the dust, the maximum explosion pressure

rise rate, and explosibility. The power and destructiveness of the explosion can be described by the scope and extent of damage after the explosion. The explosion sensitivity reflects the difficulty of dust explosion. It describes the possibility of an explosion from the perspective of accident probability,⁴ mainly characterized by the lowest ignition temperature of the dust cloud. To determine the degree of danger of pulverized coal explosion and avoid explosion, we must first understand the sensitive characteristics of dust explosion and the characteristics of the explosion intensity. Based on this, the corresponding measures can be taken to reduce casualties and property loss.⁵

The explosion of pulverized coal is a complex physical and chemical reaction process. Many scholars have conducted

Received: July 19, 2021

Accepted: September 22, 2021

Published: October 6, 2021

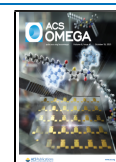


Table 1. Industrial Analysis Results %^a

| sample | proximate analysis w_{ad} (%) | | | | ultimate analysis w_{daf} (%) | | | | |
|---------|---------------------------------|----------|----------|-----------|---------------------------------|------|-------|------|-------|
| | V_{daf} | M_{ad} | A_{ad} | FC_{ad} | C | H | O | N | S_t |
| lignite | 45.4 | 1.24 | 8.07 | 45.29 | 71.97 | 4.52 | 21.04 | 1.21 | 1.26 |
| 420 °C | 27.53 | 0.27 | 8.41 | 63.79 | 73.35 | 4.01 | 19.65 | 1.57 | 1.42 |
| 520 °C | 18.21 | 0.19 | 8.82 | 72.78 | 76.58 | 3.49 | 17.42 | 1.60 | 0.91 |
| 620 °C | 15.17 | 0.14 | 9.33 | 75.36 | 79.29 | 2.81 | 15.51 | 1.52 | 0.87 |
| 720 °C | 10.2 | 0.12 | 10.62 | 79.06 | 82.84 | 2.10 | 12.92 | 1.40 | 0.74 |
| 820 °C | 4.16 | 0.09 | 10.98 | 84.77 | 90.03 | 1.83 | 6.09 | 1.37 | 0.68 |
| 920 °C | 2.45 | 0.07 | 11.37 | 86.11 | 93.68 | 1.19 | 3.14 | 1.35 | 0.64 |

^a V_{daf} is the percentage of dry ash-free volatile matter, M_{ad} is the percentage of moisture, A_{ad} is the percentage of ash, and FC_{ad} is the percentage of fixed carbon.

research on coal dust explosion sensitivity,^{6–9} explosion intensity,^{10,11} explosion flame,^{12,13} and pressure wave propagation law.^{14,15} However, research has been focused on the engineering and macrolevel. The influences of particle size and particle size dispersion of coal with different metamorphic degrees on the explosion severity have been studied.^{16,17} Researchers have analyzed the influences of particle size and concentration on the minimum ignition temperature of coal dust.^{18,19} From the perspective of experimental research and data analysis,^{20,21} most scholars have proven that coal quality indicators are the main factors influencing the explosion characteristics of coal dust, with the volatile matter having the greatest impact.²² The higher the volatile content, the lower the minimum ignition temperature of the coal dust, the easier it is to burn, and the faster the spreading of the explosion flame.^{23,24} The lower the volatile content of coal, the lower the oxygen consumption rate and heat release intensity, and the less likely it is to burn.²⁵ Compared with highly volatile coal dust, the lowest ignition energy of the low-volatile coal dust has a more significant impact on the explosion.²⁶ This is due to the synergistic behavior of combustible dust in the process of combustion and explosion. Studies on the combustion and explosibility of combustible dust have shown that the volatile point of mixed dust is lower than that of pure dust.²⁷ The reactivity of mixed dust with a combustible gas is much higher than that in the case of dust combustion and explosion reaction.²⁸ The explosion index of mixed dust is higher than that of single dust.²⁹

The coal dust heated out of the combustible gas plays a key role in the coal dust explosion. However, the mechanism of the effects of precipitation and combustion of volatile matter on the explosion characteristics of coal dust remains unclear. Therefore, it is impossible to reveal the fundamental factors and reaction mechanisms associated with the occurrence of coal dust explosion. Moreover, it is difficult to effectively predict the critical explosion conditions in an actual production environment, which limits the development of explosion suppression technologies.

This paper explores the effects of the volatile contents in raw coal and lignite on their explosion characteristics under six different pyrolysis final temperature conditions. Highly volatile lignite is subjected to high-temperature pyrolysis, and the final temperature is changed to control the contents of the volatiles in the dust. The maximum pressure of coal dust explosion in a nearly spherical space of 20 L and the maximum pressure rising rate and explosion index are used to characterize the explosion strength and pressure. Recently, this characterization has been based on explosibility, and the lowest ignition temperature of the dust cloud is used to characterize the susceptibility of an

explosion. The research results have important theoretical and practical significance in understanding the influence mechanism and occurrence mechanism of volatile matter on the explosion characteristics of coal dust. The results are expected to help improve the accuracy of coal dust explosion prediction, explore the evolution process of coal dust explosion, and efficiently develop active suppression products and technologies.

2. EXPERIMENTAL SAMPLE PREPARATION AND EXPERIMENTAL DEVICES

2.1. Experimental Sample Preparation. The experimental sample selected was lignite with high volatility. The coal sample was ground using a crusher and a ball mill and then sieved using a 200 mesh sieve to ensure that the particle size of the sample was less than 75 μm . The minus 200 mesh lignite dust was placed in a crucible and then in a muffle furnace and heated. To prevent the coal dust from oxidizing and burning with the oxygen in the furnace during the heating process, a lid was placed on the crucible to isolate it from the air. During the heating process, the heating rate was set to 10 °C/min. The termination temperature was set to 420, 520, 620, 720, 820, and 920 °C. After the muffle furnace was cooled to room temperature, the furnace was opened, the coal dust in the crucible was taken out, and an explosion characteristic experiment was conducted. The unheated coal dust sample was placed in a constant-temperature drying box and dried at a temperature of 80 °C for 10 h to reduce the influence of moisture in the coal dust on its explosion characteristics.

Industrial analysis of the experimental samples was conducted in accordance with GB 212-91 "Coal Industrial Analysis Methods." Table 1 presents the industrial analysis results. As listed in Table 1, the oxygen element content of the lignite selected in the experiment is 21.04%, indicating that there are a large number of oxygen-containing functional groups in lignite. With the increase in the pyrolysis temperature, the contents of the moisture, volatile matter, oxygen, and hydrogen elements in the sample gradually decreased, and the fixed carbon and ash content and carbon element gradually increased. During this process, the oxygen content decreased from 21.04% of the raw coal to 3.14%, the hydrogen content decreased from 4.52% of the raw coal to 1.19%, and the carbon content increased from 71.97 to 93.68%. The reduction of elements, such as hydrogen and oxygen, is due to the precipitation of a large number of oxygen-containing functional groups and alkyl side chains in the coal in the form of volatiles and their gradual consumption, while the relative contents of the fixed carbon and ash increase. The nitrogen in coal mostly exists in the form of more stable pyrrole and pyridine; therefore, the nitrogen content changes little.

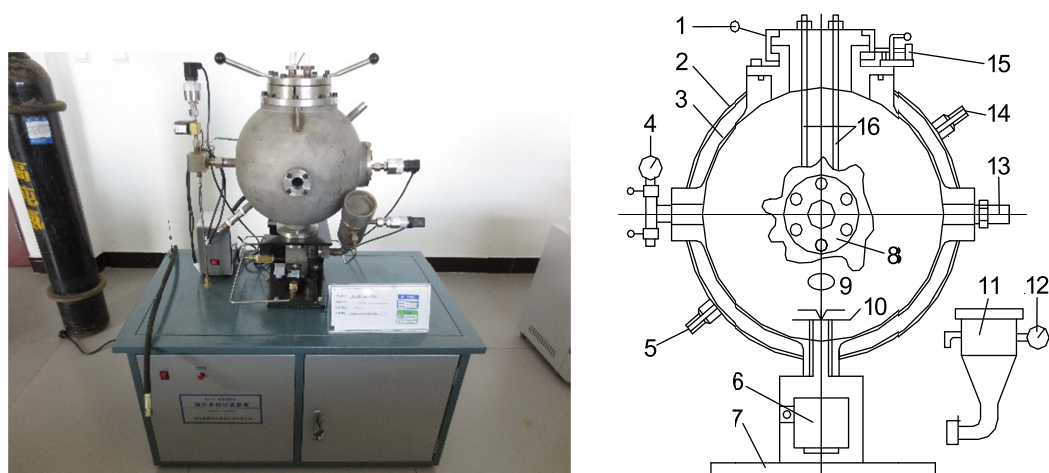


Figure 1. Structure of a 20 L near-spherical dust explosion parameter test device: 1, sealing cap; 2, sandwich coat; 3, sandwich inner sleeve; 4, vacuum gauge; 5, circulating water outlet; 6, mechanical two-way valve; 7, base; 8, observation window; 9, vacuum hole; 10, dispersion valve; 11, dust storage tank; 12, pressure gauge; 13, pressure sensor; 14, circulating water inlet; 15, safety limit switch; 16, ignition lever.

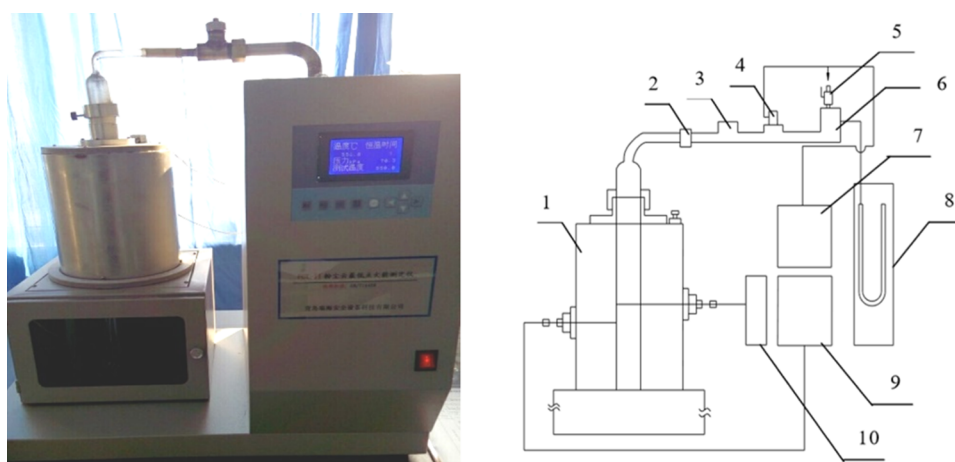


Figure 2. Structure of the coal dust cloud MITC test device: 1, heating furnace; 2, connector; 3, dust storage container; 4, solenoid valve; 5, gate valve; 6, gas storage tank; 7, regulated power supply; 8, U-shaped tube; 9, temperature controller; 10, temperature recorder.

2.2. Experimental Devices. **2.2.1. Dust Explosion Experiment Device and Operation Steps.** In this experiment, we used the MCS-II dust explosion parameter experiment device manufactured by Qingdao Ruihai Safety Equipment Technology Company Limited, China. Experiments were conducted in accordance with the International Standards EN 14034-1 2004³⁰ and EN 14034-2 2006.³¹ The device comprises a hollow stainless steel sphere, an explosion tank, an ignition system, a dust dispersion system, a control system, a data acquisition system, and a container cleaning system. The diagram of the components in Figure 1 shows the various features of the system, including automatic dust spraying, ignition data acquisition, transmission and automatic water circulation cooling, and automatic generation of a pressure–time curve. The explosion volume of the apparatus is 20 L, with an explosion pressure detection range of -0.1 to 2 MPa, an accuracy of 0.001 MPa, and a data sampling interval of 0.2 ms. The real-time values of the pressure and other data can be seen in this device. During the test, the flame resulting from the dust explosion could be observed through the glass observation window on the sphere to determine whether an explosion had occurred.

In the experiment, the dried lignite with a particle size of 75 μm and a mass of 10 g was placed in a dust storage tank. We first

tightened the lid of the dust storage tank and inserted the ignition cable into the electrode holder on the container lid. Subsequently, we closed the intake and exhaust valves, opened the vacuum valve, and started the vacuum pump. The sphere was vacuumed to -0.06 MPa. We set the ignition delay time to 100 ms on the control man–machine interface and applied compressed air at 20 bar to disperse the dust into a 20 L ball to form an atmospheric dust cloud, which ignited and triggered an explosion. The explosion parameters were automatically recorded. In the experiment, a chemical ignition method was used for the ignition, and complete combustion of 2.4 g of pyrotechnic powder could generate 10 kJ of energy. We prepared 200 mesh zirconium powder, barium peroxide, and barium nitrate in a mass ratio of 4:3:3.

After the completion of each set of tests, the container was cleaned in preparation for the next set of sample tests. During the experiment, when the lignite in the powder storage tank was injected into the 20 L ball by the compressed air, the dust cloud distribution was uneven, and the dust particles were crushed when passed through the 20 L ball nozzle. These factors affected the experimental results.^{32–35} Therefore, to ensure the accuracy of the data, each group of tests was conducted thrice to obtain the average value as the final result.

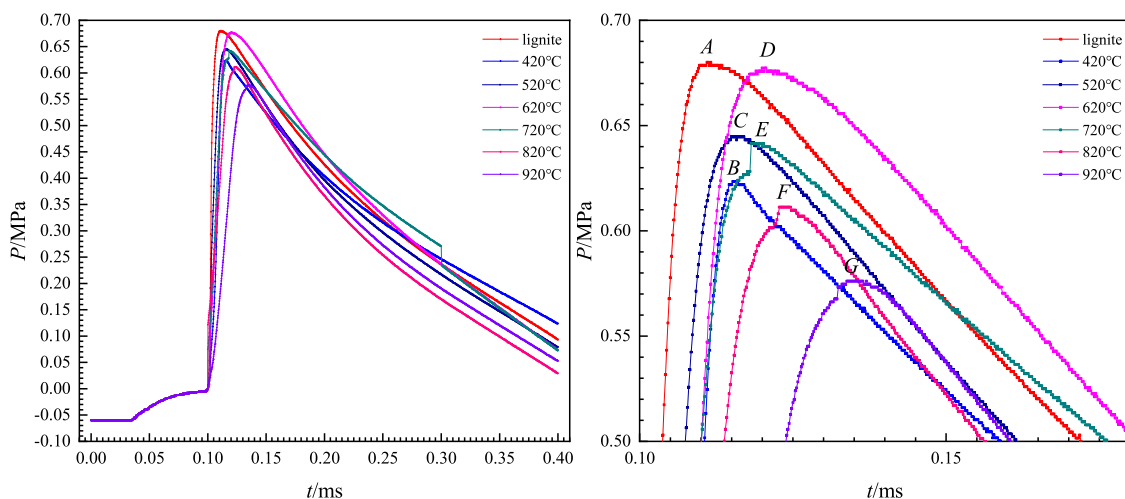


Figure 3. P - t variation curve of coal dust explosion with different volatile contents A (0.111, 0.680), B (0.1152, 0.623), C (0.115, 0.645), D (0.119, 0.676), E (0.1182, 0.641), F (0.1228, 0.6112), and G (0.1324, 0.573).

2.2.2. Dust Cloud Minimum Ignition Temperature Test Device and Operation Steps. Figure 2 shows the minimum ignition temperature test device for coal dust clouds. The device was used in accordance with the ASTM E1491-06³⁶ standard to determine the minimum ignition temperature of the dust cloud. A dust cloud minimum ignition temperature test device (model FCY-II; Qingdao Ruihai Safety Equipment Technology Co. Ltd.) was used, as shown in Figure 2. It is composed of a heating furnace, a dust spraying system, a temperature control system, and a temperature recording system. The operational temperature of the device ranges from room temperature to 1000 °C, with dust pressures ranging between 0.08 and 0.12 MPa.

During the experiment, a certain amount of lignite dust was first placed in the storage dust container. As the temperature of the heating furnace approached the setpoint, the inflation solenoid valve was opened to adjust the pressure of the gas storage tank to the intended dust spray pressure. The instrument entered the stage of constant-temperature control once the heating furnace reached the set temperature. After a set duration of time, the dust spraying solenoid valve was opened to spray coal dust into the heating furnace to form a coal dust cloud. The distance between the outlet of the solenoid valve and the dust storage container was less than 500 mm to enable uniform dispersion of the coal dust clouds. The heating furnace was installed on the support seat, and a reflector was installed under the heating quartz tube. The flame was observed through the glass tube for any propagation beyond the lower end of the heating tube, and the temperature of the heating furnace was continuously reduced to increase the test accuracy. After 10 experiments, if all of the samples were ignited successfully, the minimum temperature was then recorded as the minimum ignition temperature of the coal dust cloud.

3. RESULTS AND DISCUSSION

3.1. Influence of Volatile Matter on the Intensity of Dust Explosion. A ball mill and a sieving instrument were used to screen the coal samples, and lignite coal dust samples with minus 200 meshes were obtained to study the influence of the volatile content in lignite on its explosive strength. The coal dust was subjected to high-temperature pyrolysis. The final temperature was changed to obtain coal dust with different volatile contents and an explosion intensity parameter test experiment

was conducted. Figure 3 shows the explosion pressure changes with time. Figure 4 shows the explosion pressure rise rate changes with time. The coal dust explosion index K_{st} is an important parameter to determine the level of coal dust explosion.

The calculation formula of the dust explosion index is

$$K_{st} = (dP/dt)_{\max} V^{1/3} \quad (1)$$

where K_{st} is the dust explosion index, $(dP/dt)_{\max}$ is the maximum pressure rise rate of the dust, and V is the volume of the reaction vessel.

The calculation by eq 1 shows that the coal dust explosion index is directly proportional to the rate of increase in the maximum explosion pressure of coal dust. Table 2 presents the calculation results.

From Figures 3 and 4 and Table 2, we find that the final pyrolysis temperature directly affects the volatile content of lignite. As the final pyrolysis temperature increases, the volatile content of dust gradually decreases. When the volatile content is reduced from 45.4 to 2.45%, the average rate of change is 5.435%. However, the volatile content of lignite has a significant effect on the rate of increase of the maximum explosion pressure. When the final pyrolysis temperature increases to 620 °C, the rising rate of the maximum explosion pressure of the dust cloud decreases by 25.52%. When the final temperature of the pyrolysis is increased to 820 °C, the rising rate of the maximum explosion pressure of the dust cloud decreases rapidly, decreasing by 44.44%, and then decreases gradually. This is consistent with the changing trend of the influence of the final pyrolysis temperature on the volatile content of the dust. This shows that the change in the volatile matter content directly affects the rate of increase in the maximum explosion pressure of dust and that the volatile matter can promote the combustion and explosion process.

The explosion index of the experimental sample was in the range of 0–20, and the explosion characteristic was weak. This shows that although the greater the volatile content, the more violent the dust explosion combustion reaction, the lower the volatile content in the dust, and the lower the explosion index. Under this experimental condition, the explosion characteristics of the dust were relatively weak, and they were all in a relatively safe state.

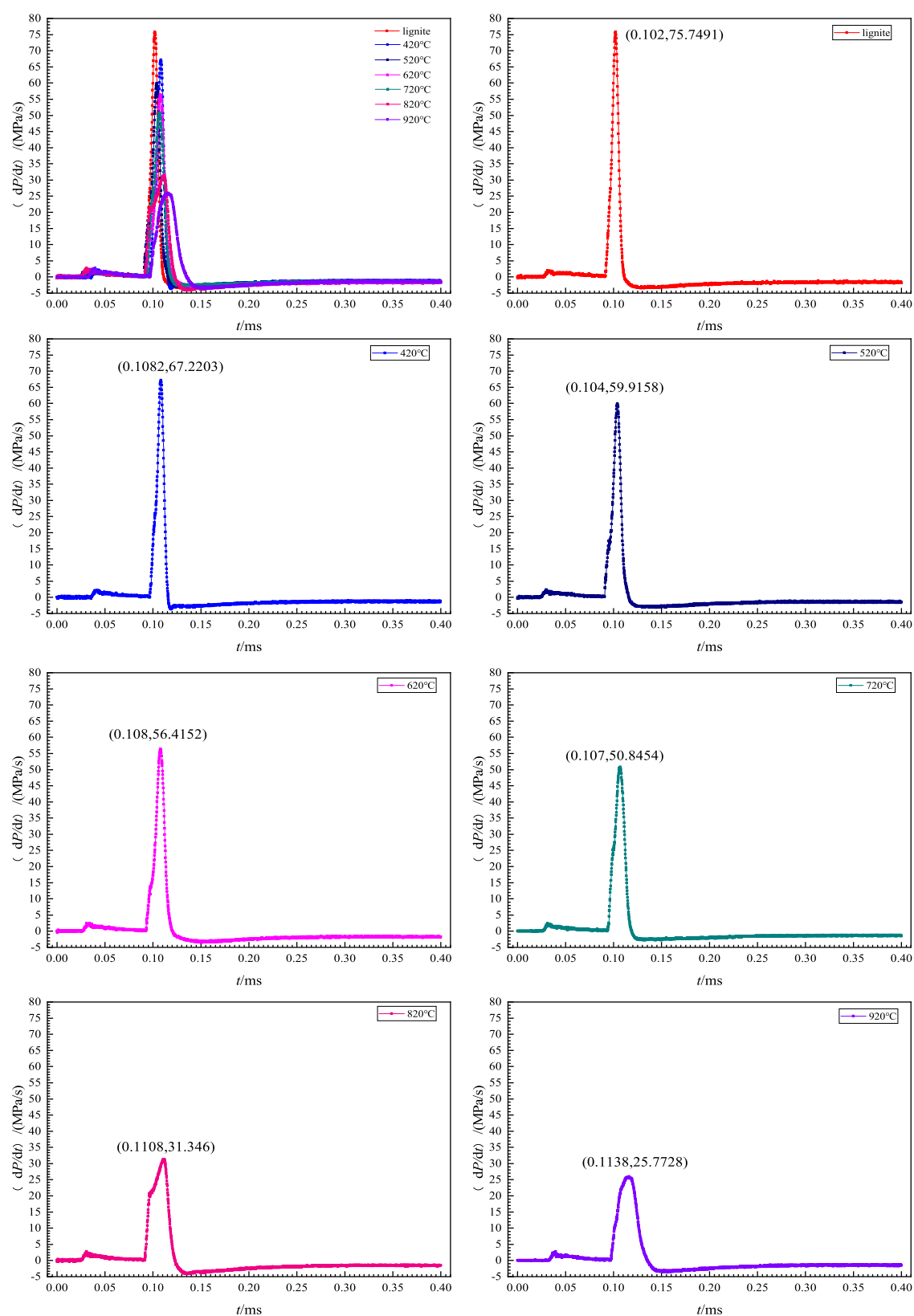


Figure 4. (dP/dt) – t variation curve of coal dust explosion with different volatile contents.

3.2. Influence of Volatile Matter on the Explosibility of Dust. Based on the pressure measured during the experiment, as described in Section 3.1, and the calculations made using eq 2, we judge whether dust with different volatile contents is explosive. Table 3 presents the test and calculation results.

$$PR = (P_{ex,a} - P_{ignitor}) / P_{ignitor} \quad (2)$$

where PR is the pressure ratio, $P_{ex,a}$ is the maximum absolute pressure produced during a single deflagration test, and $\Delta P_{ignitor}$ is the pressure rise above $P_{ignitor}$ due to the activation of the

Table 2. Measured Data of Coal Dust Explosion Pressure Characteristics with Different Volatile Contents^a

| sample | V_{daf} | P_{max} | $(dP/dt)_{max}$ | K_{st} |
|---------|-----------|-----------|-----------------|----------|
| lignite | 45.4 | 0.68 | 75.7491 | 1.514982 |
| 420 °C | 27.53 | 0.6234 | 67.2203 | 1.344406 |
| 520 °C | 18.21 | 0.6446 | 59.9158 | 1.198316 |
| 620 °C | 13.07 | 0.6759 | 56.4162 | 1.128304 |
| 720 °C | 5.31 | 0.6414 | 50.8454 | 1.016908 |
| 820 °C | 3.02 | 0.6112 | 31.346 | 0.62692 |
| 920 °C | 2.45 | 0.5732 | 25.7728 | 0.515456 |

^a P_{max} is the maximum explosion pressure.

Table 3. Explosibility of Coal Dust with Different Volatile Contents

| sample | V_{daf} | P_{ex} | PR | whether explosive or not |
|---------|-----------|----------|-------|--------------------------|
| lignite | 45.4 | 0.661 | 6.61 | explosive |
| 420 °C | 27.53 | 0.6129 | 5.129 | explosive |
| 520 °C | 18.21 | 0.631 | 5.31 | explosive |
| 620 °C | 15.17 | 0.6575 | 5.575 | explosive |
| 720 °C | 10.2 | 0.6282 | 5.282 | explosive |
| 820 °C | 4.16 | 0.6024 | 5.024 | explosive |
| 920 °C | 2.45 | 0.5697 | 5.697 | explosive |

ignitor(s) with no dust present in the chamber. $P_{ignition}$ is the absolute pressure in the vessel at the time of ignition. When $PR \geq 2$, dust is explosive.^{30,31}

From Table 3, we find that all of the experimental samples are explosive. Even if the volatile content is less than 5%,³⁷ the dust is still explosive. The explosion mechanism can be, mainly divided into two: thermal explosion reaction mechanism and chain reaction mechanism. According to these mechanisms, the explosion of coal dust is the result of the precipitation and combustion of volatiles. In the case of low-volatile matter, volatile analysis and combustion, group distribution, migration, and transformation are important factors that make the dust explosive. Therefore, both the content of volatile matter and the change law of the volatile matter analysis are factors influencing the explosibility of dust.

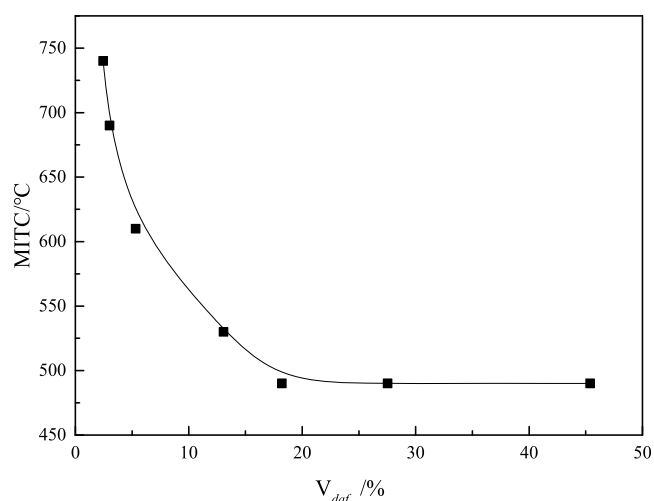
3.3. Influence of Volatile Matter on the Minimum Ignition Temperature of Dust Cloud. A ball mill and a sieving instrument were used to screen the coal sample, and a lignite coal dust sample with minus 200 meshes was prepared to study the influence of volatile content in lignite on its explosive sensitivity. The coal dust was pyrolyzed by changing the final temperature to obtain coal dust with different volatile contents and the lowest ignition temperature of the dust cloud was used to evaluate its explosion sensitivity. Table 4 lists the measured results. Figure 5 shows the change rule.

From Table 4, when the volatile content in lignite is reduced from 45.4 to 18.21%, the minimum ignition temperature of the dust cloud remains unchanged at 490 °C. When the final pyrolysis temperature applied to the coal dust is increased, its volatile content is reduced. When the volatile content in lignite decreases from 18.21 to 2.45%, the minimum ignition temperature of the dust cloud rises, increasing by 51.02%. This shows that when the volatile content is in the range of 45.4–18.21%, although the volatile content gradually decreases, the change in the volatile content and the separated flammable volatile gas components at this stage have little effect on the minimum ignition temperature of the dust. When the volatile content is in the range of 18.21–2.45%, the higher the volatile

Table 4. Measured Data of the Minimum Ignition Temperature of Coal Dust Cloud with Different Volatile Contents^a

| V_{daf} (%) | gradient (%) | MITC (°C) | gradient (%) |
|---------------|--------------|-----------|--------------|
| 45.4 | | 490 | |
| 27.53 | 39.36 | 490 | 0 |
| 18.21 | 33.85 | 490 | 0 |
| 13.07 | 16.69 | 530 | 8.16 |
| 5.31 | 32.76 | 610 | 15.09 |
| 3.02 | 59.22 | 690 | 13.11 |
| 2.45 | 48.32 | 740 | 7.25 |

^aMITC is the minimum ignition temperature of the coal dust cloud.

**Figure 5.** Variation curve of the MITC of coal dust with different volatile contents.

content, the easier the ignition of the dust cloud, and the lower the volatile content, the higher the minimum ignition temperature of the dust cloud, and the less likely the ignition of the dust. When the pyrolysis temperature of the coal sample is in the range of 620–920 °C, the volatile content first decreases rapidly. When the pyrolysis temperature reaches 820 °C, it gradually decreases. The minimum ignition temperature of dust first increases rapidly. When the pyrolysis temperature is 720 °C, it gradually increases. It is different from the rate of change in the volatile content. This shows that although the volatile content in the dust is a factor that describes the nature of dust combustion and explosion, in the early stage of dust combustion and explosion, the type, content, and rate of flammable volatile gas the sample is subjected to are the main factors determining the minimum ignition temperature of the dust cloud.

3.4. Influence of Volatile Components on the Minimum Ignition Temperature of Dust Cloud. To further study the influence of volatiles in the coal dust on the minimum ignition temperature of the dust cloud, the experimental samples obtained, as described in Section 2.1, were placed in a vacuum tube furnace with the heating rate set to 10 °C/min and the final pyrolysis temperature to 920 °C for high-temperature pyrolysis. A gas chromatograph was used to quantitatively analyze the volatile gases produced during the pyrolysis of the samples.

The volatile gases that can be precipitated during coal dust heating mainly include H_2 , CO , CH_4 , CO_2 , C_2H_4 , C_2H_6 , and other gases. Since the precipitation contents of the other gases are relatively low, this study mainly focuses on the change rule of

the precipitation contents of H₂, CO, CH₄, and CO₂ at different temperatures. Figure 6 shows the volatile component content of

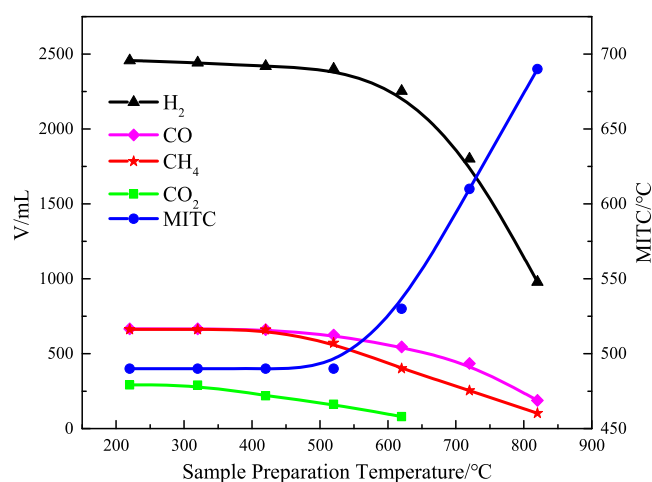


Figure 6. Volatile composition of the sample and the change curve of the minimum ignition temperature at different pyrolysis temperatures.

the sample and the change curve of the minimum ignition temperature at different processing temperatures. As shown in Figure 6, in the low-temperature section (less than 520 °C), the content of combustible volatile gases precipitated from the sample is low, the content of volatiles remaining in the sample is high, and the content of the precipitable gas components is high. With the increase in the pyrolysis temperature, the volatile content decreases and the amount of gas that can be precipitated decreases. Since coal dust explosion is essentially a gas explosion, the contents of volatile and precipitable gas in the sample after the high-temperature treatment decrease, leading to an increase in the minimum ignition temperature.

4. CONCLUSIONS

We conducted experiments on highly volatile lignite coal dust samples using a 20 L spherical dust explosion parameter measuring device and dust cloud minimum ignition temperature testing device to analyze the influence of volatile content on its pressure characteristics and explosion possibility and the influence of sensitive features. Gas chromatography was applied to determine the volatile gas composition content and thus analyze the influence on the minimum ignition temperature of the dust cloud. The following conclusions can be drawn from the study:

- (1) The higher the final pyrolysis temperature, the lower the contents of volatile matter, moisture, and oxygen and hydrogen elements. Moreover, the fixed carbon and ash contents as well as the carbon element gradually increased. When the volatile content of lignite was reduced from 45.4 to 2.45%, the average change rate was 5.435%. The volatile matter in lignite coal dust had a more evident influence on the rate of increase in the maximum explosion pressure. When the volatile content was reduced from 45.4 to 2.45%, the maximum explosion pressure rise rate was reduced by 65.976%. During the experiment, the explosion index of all the samples was in the range of 0–1.6, and the explosion intensity was relatively weak. Within this range, the higher the volatile content, the greater the explosion index and the more

violent the reaction. The lower the volatile content, the lower the explosion index.

- (2) All of the experimental samples were explosive. The volatile content of the experimental samples was found to be in the range of 2.45–45.4%; however, the pressure ratio was consistently greater than 2.
- (3) When the volatile content in lignite was reduced from 45.4 to 18.21%, the minimum ignition temperature of the dust cloud remained unchanged, i.e., 490 °C. With the decrease in the volatile content, its content reduced from 18.21 to 2.45%. Within this range, the minimum ignition temperature of the dust cloud increased by 51.02%, and the volatile content at this stage had a significant effect on the minimum ignition temperature of the dust cloud.
- (4) The analysis of the contents of H₂, CO, CH₄, and CO₂ precipitated from the experimental samples showed that when the final pyrolysis temperature is lower than 520 °C, the amount of each gas precipitated from the samples is low. Therefore, the minimum ignition temperature of the dust cloud did not change much at this stage. With the increase in the final pyrolysis temperature, the content of the precipitated volatile gas increased, leading to a decrease in the remaining precipitated volatile gas and in turn to an increase the degree of dust cloud being ignited and the minimum ignition temperature.

In this study, the influence of volatile matter on the dust explosion characteristics was analyzed from two aspects: the volatile content in the dust and the contents of volatile components. Our results have important theoretical value in effectively predicting the possibility of coal dust explosion and the degree of damage in an actual production environment. The effective development and use of explosion-proof products and technologies have fundamental significance. Because of the limitations of the existing experimental conditions, it is only possible to simulate the heating conditions of the dust in the early stages of the explosion. For the early stage of the explosion, the composition and content of the volatile gases precipitated by the rapid heating of dust should be further studied.

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Notes

The authors declare no competing financial interest. The data used to support the findings of this study are available from the corresponding author upon request.

ACKNOWLEDGMENTS

This work was supported by the Chinese National Natural Science Foundation (grant number 51774168).

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